

Energy efficiency enhancement using dynamic voltage restorer (DVR)

Muhammad Murtadha Othman¹, Nik Muhamad Lokman Fahmi Nek Rakami², Zulkiffli Abdul Hamid³, Ismail Musirin⁴, Mohammad Lutfi Othman⁵

^{1,2,3,4} Faculty of Electrical Engineering, Universiti Teknologi MARA, Malaysia

⁵ Centre for Advanced Power and Energy Research and Department of Electrical and Electronics Engineering, Universiti Putra Malaysia, Malaysia

Article Info

Article history:

Received Jul 27, 2018

Revised Jan 12, 2019

Accepted Mar 15, 2019

Keywords:

Dynamic voltage restorer (DVR)

Energy efficiency

Harmonic

Hysteresis Voltage Control

Voltage Sag

Voltage Swell

ABSTRACT

Dynamic voltage restorer (DVR) is a device that can compensate harmonic, voltage sag and voltage swell condition that exists in a three-phase system. Other than that, DVR can also be used to enhance the energy efficiency or energy saving by reducing excessive amount of incoming power via the reduction incoming voltage at allowable limit. The DVR can inject the required voltage in the system so that the interruption of supply voltage can be compensated. The compensation of voltage supply interruption is improved based on the hysteresis voltage output of controller used in the DVR to detect the difference between reference voltage and disrupted voltage. The hysteresis voltage control mainly controlled by relays switching so that the signal can be sent to IGBT switches controller. The hysteresis voltage control and unipolar SPWM is supplied to control the IGBT switches by the DC supply for voltage interruption compensation. The unipolar SPWM technique converts the DC supply voltage into AC supplied voltage, thus making the DVR injection become easier to inject the AC voltage into the system to compensate voltage sag and voltage swell.

Copyright © 2019 Institute of Advanced Engineering and Science.
All rights reserved.

Corresponding Author:

Muhammad Murtadha Othman,
Faculty of Electrical Engineering,
Universiti Teknologi MARA,
40450 Shah Alam, Selangor, Malaysia.
Email: mamat505my@yahoo.com

1. INTRODUCTION

Ideally, electricity should be provided efficiently and without any interruptions required or desired by utilities and users. Without the smooth continuity of electricity supply, the consumers may not receive their power demands efficiently [1-5]. However, the utilities may find it difficult to provide a clean and continuous electric supply due to the presence of harmonic distortion, voltage sag and voltage swell. The increasing usage of nonlinear loads in the industry often making the harmonic distortion level becomes critical [6-10]. Consequently, this will introduce inefficient energy consumption to the consumers.

In addition, electricity plays an important role in productivity from many industrialized countries. Therefore, the usage of power electronic components used to control the non-linear load in the industrialized countries will also be increased. However, these components are sensitive devices that are requiring a constant of voltage magnitude, voltage frequency and voltage phase [11]. They required a good power quality in order to avoid any failure in the power electronic components and electrical equipment in such a way that it will breakdown in electrical equipment and eventually damage the electrical equipment as well as slowly shorten their lifespan [12]. Therefore, this issue is not a trivial problem for countries that are developing their products in the industry. Voltage sag and swell are the main issue that may cause the power quality problem [13-17]. DVR is one of the wise solutions used to mitigate the power quality problem. It is

able to compensate the voltage sag, voltage swell and also harmonic condition by injecting their voltage in series synchronously with the system to ensure the smoothness of power quality can be maintained [18-19]. Generally, there are three basic control strategies for a DVR such as pre-sag compensation, in-phase compensation and energy optimization compensation [20].

In pre-sag compensation, the supply voltage is consistently monitored and initiates the injection before the occurrence of voltage sag and it also able to compensate the phase shift of incoming voltage. On the other hand, the DVR with in-phase compensation will only compensate the magnitude of voltage sag. The DVR voltage is continuously in phase with the measured incoming voltage regardless the phase shift of incoming voltage. With energy optimization compensation, the voltage is injected with its phase angle in quadrature with load current to reduce the use of real power. Therefore, this strategy will reduce the energy consumption of energy storage. In a DVR controller, it uses the hysteresis voltage control to detect the disrupted incoming voltage and supplied to the Insulated Gate Bipolar Transistor (IGBTs) as switching devices for voltage-sourced converter (VSC)[21]. Specifically, DVR compensate the interruption of incoming voltage by referring to the unipolar SPWM coming from the IGBT switches.

Other than that, the DVR plays an important role in energy efficiency enhancement of a three-phase system. The energy consumption in a non-linear load can be reduced by increasing their energy efficiency via reduction of incoming voltage at allowable limit such as 200V per-phase. With the reduced input voltage at the permissible limit, the load may function properly and operates at lower energy consumption. Thus, the energy efficiency of the system can be enhanced.

2. RESEARCH METHOD

Figure 1 shows a schematic diagram of dynamic voltage restorer (DVR) connected in series with the sensitive load in a distribution system. The DVR contains of voltage-source converter (VSC), hysteresis voltage control, a booster transformer and also passive filter used to filter any harmonic component exists in the system. The DVR will inject a three-phase of AC voltage in series synchronously with the supplied voltage for the occurrence of voltage sag or voltage swell. This signifies that whenever the quality of supplied voltage is interrupted or distorted, the DVR can restore the quality of the voltage at the load side by controlling the voltage amplitude, phase angle and frequency of voltage.

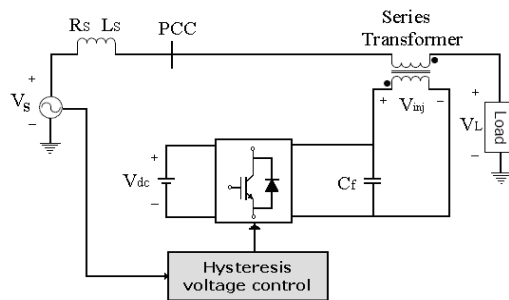


Figure 1. Basic principle of dynamic voltage restorer

The ensuing explanation represents the operation of DVR. Firstly, the DVR will receive a signal from point representing as the current situation of incoming supply voltage. Secondly, the DVR will detect the incoming supply with power quality problem condition converted as a small signal coming from point B and comparison is made between incoming voltage supply signal (V_{Line}) having power quality problem and reference voltage in order for the hysteresis voltage controller to operate and mitigate the waveform segment of incoming voltage supply having the power quality problem. This operation is performed by the DVR indicated by label C in Figure 2. In particular, the difference between reference voltage and incoming voltage supply having power quality problem will transmit as a difference signal to perform the switching in relays for later use in mitigating and compensate the power quality problem incurred in the incoming voltage supply. The hysteresis switching relays will instruct the operation of IGBT switches labeled as D to produce the unipolar SPWM signal from DC supply voltage into AC supply voltage [22]. Lastly, the IGBT switches will inject its converted supply voltage into the system to compensate the voltage sag and swell in the system through the three-phase isolation transformer labeled as E.

In Figure 3, there are six IGBT switches connected in a three-phase bridge connection. The difference or error signal will drive the IGBT switches to produce the unipolar SPWM in discrete-time waveform at point I to inject and compensate the voltage sag or swell occurred in the system [25]. The voltage magnitude of unipolar SPWM can reach up to 700V originated from the DC supply voltage at point 1 and point 2. This implies the IGBT switches convert the DC voltage supply into AC output voltage of unipolar SPWM.

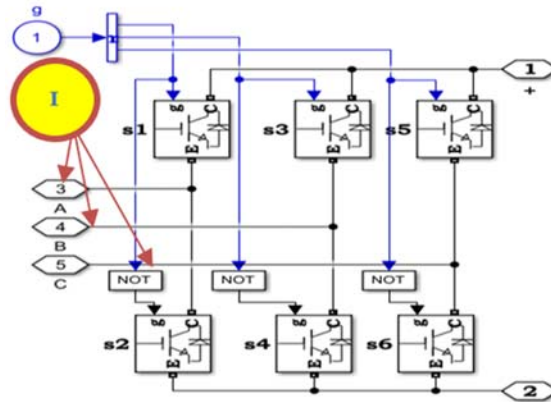


Figure 3. IGBT switches

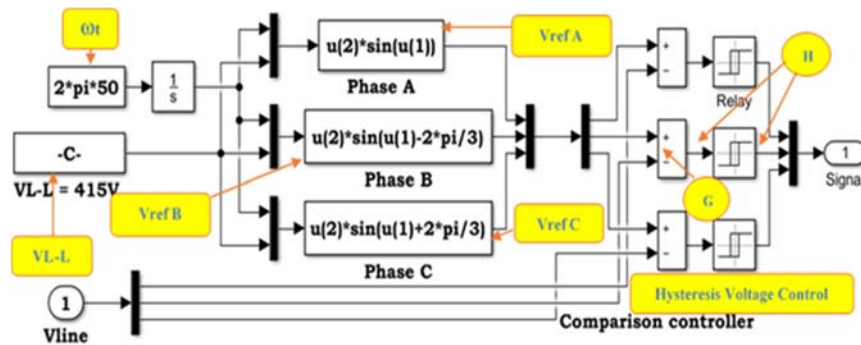


Figure 4. DVR controller circuit

2.4. Three-phase isolation/booster transformer

The three-phase isolation or booster transformer is connected in series with the three-phase system and it is labeled as E in Figure 2. It is used to inject the AC voltage of unipolar SPWM waveform into the system so that the incoming voltage sag or swell can be compensated. The secondary-side of transformer is in wye connection and the primary-side of transformers is connected in series with the three-phase system.

The fixed value of parameters is set into the transformer so that the desired output waveform can be obtained. The nominal power and frequency are 4000VA and 50Hz, respectively. It is specified for the transformer and it is depending on the KVA rating of loading condition. The primary (1) and secondary (2) side of transformer is composed with the parameters setting of voltage, resistance, and inductance that is 508V, 0.02p.u. and 0.02p.u., respectively. The saturation characteristic, core loss resistance and initial flux are set in accordance to the standard type of three-phase isolation transformer available in the market. The three-phase isolation transformer received the unipolar SPWM of discrete-time waveform to compensate the distorted signal of an AC sinusoidal continuous-time waveform happened in the three-phase system.

2.5. Three-phase isolation/booster transformer

The passive filter labeled as B in Figure 2 is comprised of resistor and capacitor used to filter the harmonic components originated from the voltage compensation injected by the three-phase isolation

transformer. The RC branch type consisting with resistor and capacitor is selected in such a way to operate the passive filter. The resistance and capacitance values are set as 1Ω and $100\mu\text{F}$, respectively for the RC branch type of passive filter.

3. RESULTS AND ANALYSIS

The operating performance of three-phase dynamic voltage restorer (DVR) has been carried-out on a case study of three-phase system consisting with 8.14 kVA rating of power supply and 7.56 kVA rating of loading condition shown in Figure 2. The DVR is responsible to mitigate the three power quality problems of voltage sag, voltage swell and harmonic. It is worthwhile to mention that the main task of DVR controller is to produce the difference or error signal between the reference voltage and interrupted incoming voltage. The error signal is then received by the IGBT switches to produce the AC unipolar SPWM. The AC unipolar SPWM is transferred to the three-phase isolation transformer to convert and compensate the distorted part of incoming voltage. Figure 5 shows the fixed reference voltage of 415V taken from Vref A, Vref B and Vref C in DVR controller circuit shown in Figure 4.

Figure 6 shows the difference between the fixed voltage reference and distorted incoming voltage at 0.1 second until 0.15 second taken from Vline and Vref in Figure 4. The comparison is made between the two waveforms to initiate the operation of DVR controller. The incoming voltage distortion is one of the power quality problems that may instigate ineffective operation of load hence shorten the lifespan performance. As a result, the comparison between the reference voltage and distorted incoming voltage may yield to hysteresis signal and difference or error signal at the input and output of point H in Figure 4, respectively. The hysteresis signal and difference or error signal are shown in Figure 7 and the duration for both signals to operate is between 0.1 second to 0.4 second depending to the duration of distorted incoming voltage discussed beforehand.

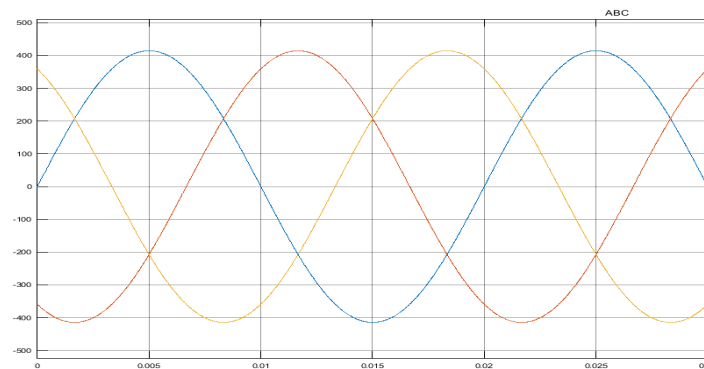


Figure 5. Three-phase fixed reference voltage.

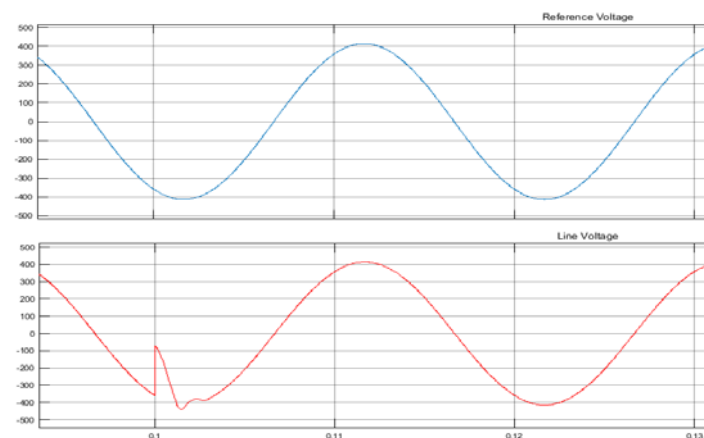


Figure 6. Comparison between the (a) fixed reference voltage, and (b) distorted incoming voltage waveform.

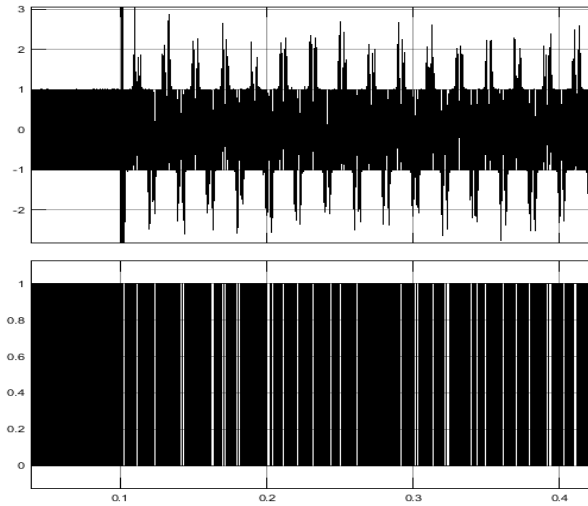


Figure 7. (a) Hysteresis signal, and (b) difference or error signal subject to the comparison between the fixed reference voltage and distorted incoming voltage.

The width for every pulse of difference or error signal is representing the magnitude distortion of voltage. The difference or error signal is obtained from the switching relay and is used to trigger the IGBT switches to convert from DC voltage supply and then inject the AC unipolar SPWM. By referring to Figure 3, the difference or error signal is transferred via point G of IGBT switches circuit. The three-phase AC unipolar SPWM is shown in Figure 8 and these waveforms are obtained from point I in Figure 3. Eventually, the IGBT controller will inject the AC unipolar SPWM into the three-phase system merely to compensate the magnitude distortion of AC incoming voltage.

Further analysis to investigate effective performance of DVR is done for two different cases of voltage sag and swell. The first analysis is done based on the 80% of voltage sag happened at duration 0.1 second to 0.15 second shown in Figure 9(a). Hence, the three-phase incoming voltage is reduced to 0.2 p.u. during the sagging condition. Therefore, the DVR controller detect the 0.2 p.u. of incoming voltage sag and compared it with the fixed reference voltage of 1.0 p.u. that eventually driven the IGBT switches to inject AC unipolar SPWM to compensate 0.8 p.u. remaining magnitude of voltage sag shown in Figure 9(c). The improved incoming voltage subject to the compensation made by the DVR is shown in Figure 9(b).

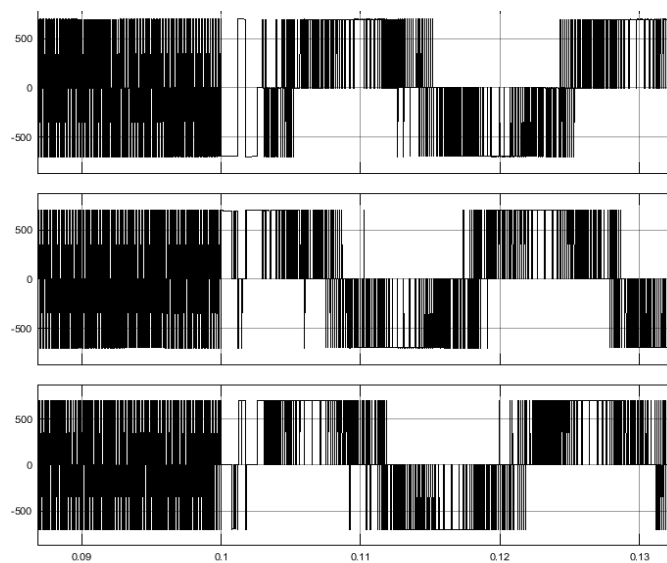


Figure 8. The AC unipolar SPWM of the IGBT controller for (a) Phase A, (b) Phase B, and (c) Phase C.

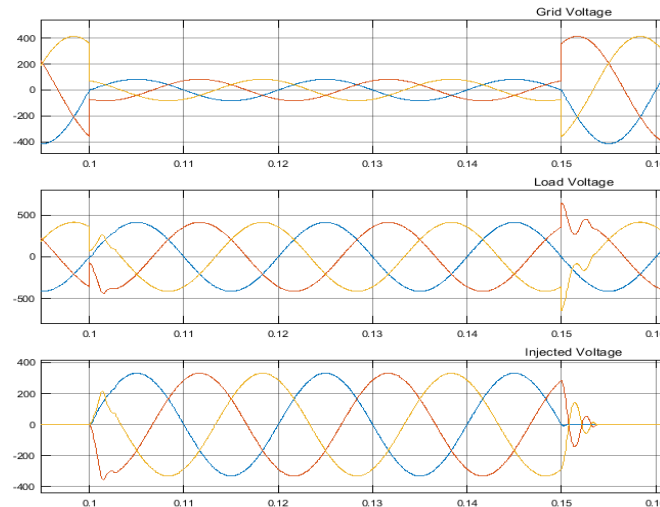


Figure 9. DVR performance at 80% of voltage sag (a) before compensation, (b) after compensation, and (c) voltage compensation.

The robustness of DVR is also investigated and verified based on the cases of 80% in the occurrence of voltage swell shown in Figure 10(a). The duration of 80% of voltage swell is 0.1 second to 0.15 second. The DVR inject AC unipolar SPWM to compensate 0.8 p.u. remaining magnitude of voltage swell to the three-phase system for compensation as shown in 18(c). The improved version of incoming voltage compensation done by the DVR can be observed in 18(b). The results proof that the DVR is capable to effectively mitigate the voltage swell at any level of percentage.

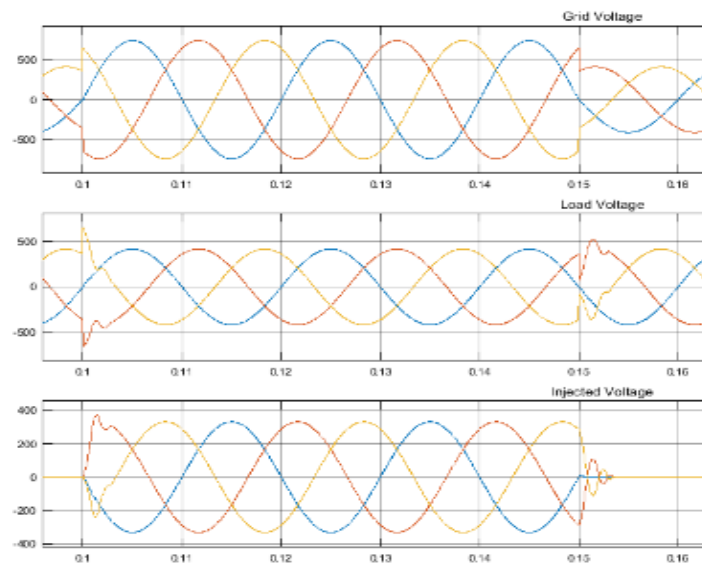


Figure 10. DVR performance at 80% of voltage swell (a) before compensation, (b) after compensation, and (c) voltage compensation.

Figure 11(a) shows the unbalanced incoming voltage waveform caused by the harmonic injected from the source. The DVR controller will operate the IGBT switches to produce AC unipolar SPWM for mitigating the unbalanced incoming voltage condition caused by injected harmonic. Figure 11(c) shows the AC voltage injected from the three-phase isolation transformer and provides the mitigated unbalanced

incoming voltage as shown in Figure 11(b). Finally, the DVR capable to reduce the total harmonic distortion (THD) at every phase from 20.62% to the range of 0.21% to 0.23%. The results are depicted and summarized in Table 1. Thus, the DVR is also performed effectively in producing a smooth sinusoidal waveform of three-phase incoming voltage subsequent to the harmonic mitigation. By mitigating the harmonic, the power losses in the system will be reduced. Rather than mitigating the voltage sag, voltage swell, and unbalanced voltage condition caused by the harmonic condition, the DVR can also be used for energy saving purposes by reducing the real power and reactive power at allowable level injected to the three-phase system. Table 2 shows the results of energy saving corresponding to the incoming real and reactive powers subject to the reference voltage of 415V and 346.5V set by the DVR. The results show that the incoming real and reactive powers are reduced from 2244W and 803.9VAR to 1874W and 671.5VAR in accordance to the reduction of reference voltage from 415V to 346.5V specified at the DVR. The reference voltage is reduced to 346.5V because it is an permissible limit for the operation of any electrical equipments. The incoming power saving is obtained from 16.49% and 16.47% for the reduction of real power and reactive power, respectively performed by the DVR. This signifies that the voltage reduction performed by the DVR is capable to produce a power saving to the incoming of the three-phase system.

Table 1. Total harmonic distortion for every phase before and after compensation using DVR

Voltage	THD before compensation	THD after compensation
Phase A	0.2062	0.002104
Phase B	0.2062	0.002178
Phase C	0.2062	0.002343

Table 2. Power at 415V and 346.5V of reference voltage

Power	Vref = 415V	Vref = 346.5V	Power Saving Percentage (%)
Real Power (W)	2244	1874	16.49
Reactive Power (VAR)	803.9	671.5	16.47

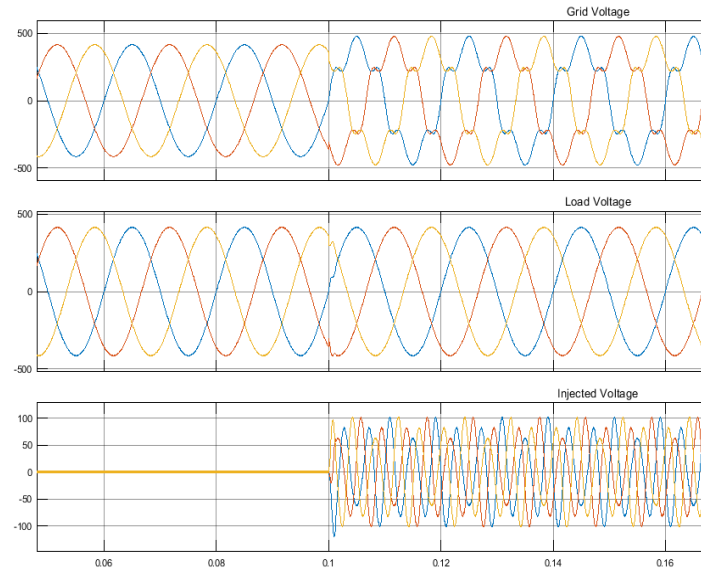


Figure 11. DVR performance at unbalanced voltage (a) before compensation, (b) after compensation, and (c) voltage compensation.

4. CONCLUSION

In this study, the DVR plays many important roles in enhancing power quality and also enhancing energy efficiency. The hysteresis voltage control was used in this study as a DVR controller to learn how the controller operates during the voltage sag, voltage swell, unbalanced voltage occurrence occurs in the system. In addition, by reducing the excessive amount of incoming voltage, it can also decrease the power consumption at the incoming side. The fixed reference voltage was reduced at permissible limit in order to

reduce the power consumption at the incoming side. By doing this operation, the DVR will assume the system condition as a voltage swell condition that occurs in the system and will try to reduce the excessive amount of incoming voltage to compensate the voltage swell condition. Therefore, the cost of power consumption of the non-linear load is reduced and the energy efficiency of the load is enhanced.

ACKNOWLEDGEMENT

This research was supported by the Long-Term Research Grant (LRGS), Ministry of Education Malaysia for the program titled "Decarbonisation of Grid with an Optimal Controller and Energy Management for Energy Storage System in Microgrid Applications" with project code 600-IRMI/LRGS 5/3 (001/2019). The authors would also like to acknowledge The Institute of Research Management & Innovation (IRMI), Universiti Teknologi MARA (UiTM), Shah Alam, Selangor, Malaysia for the facilities provided to support on this research.

REFERENCES

- [1] N. D. Tleis, *Power Systems Modelling and Fault Analysis*. 2008.
- [2] K. Hinton, J. Baliga, M. Feng, R. Ayre, and R. S. Tucker, "Power consumption and energy efficiency in the internet," *IEEE Network*, vol. 25, no. 2, pp. 6-12, 2011.
- [3] H. Zhao, Q. Wu, S. Hu, H. Xu, and C. N. Rasmussen, "Review of energy storage system for wind power integration support," *Applied energy*, vol. 137, pp. 545-553, 2015.
- [4] S. Kakran, and S. Chanana, "Smart operations of smart grids integrated with distributed generation: A review," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 524-535, 2018.
- [5] Y. Kuang, Y. Zhang, B. Zhou, C. Li, Y. Cao, L. Li, and L. Zeng, "A review of renewable energy utilization in islands," *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 504-513 2016.
- [6] N. Ciurro, "Harmonics in industrial power systems," *EC M Electr. Constr. Maint.*, 2009.
- [7] A. Kalair, N. Abas, A. R. Kalair, Z. Saleem, and N. Khan, "Review of harmonic analysis, modeling and mitigation techniques," *Renewable and Sustainable Energy Reviews*, vol. 78, pp. 1152-1187, 2017.
- [8] N. R. Kalaskar, and R. Holmukhe, "Report on Power Compensation and Total Harmonic Distortion level Analysis," *International Journal of Electrical and Computer Engineering*, vol. 6, no. 6, pp. 2577, 2016.
- [9] D. Fallows, S. Nuzzo, A. Costabeber, and M. Galea, "Harmonic reduction methods for electrical generation: a review," *IET Generation, Transmission & Distribution*, vol. 12, no. 13, pp. 3107-3113, 2018.
- [10] R. P. B. da Silva, R. Quadros, F. P. Santilio, L. C. P. da Silva, B. C. Carvalho, and A. B. de Vasconcellos, "Effects of Electronic Loads on Electrical Measurements, Power Quality and Billing," *Journal of Control, Automation and Electrical Systems*, vol. 28, no. 5, pp. 654-663, 2017.
- [11] F. C. De la Rosa, *Harmonics and Power Systems*. 2006.
- [12] J. Arrillaga, "Power quality," in *Systems, Controls, Embedded Systems, Energy, and Machines*, 2017.
- [13] M. H. J. Bollen, *Understanding power quality problems: Voltage sags and interruptions*. 1999.
- [14] T. Kang, S. Choi, A. S. Morsy, and P. N. Enjeti, "Series voltage regulator for a distribution transformer to compensate voltage sag/swell," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 6, pp. 4501-4510, 2017.
- [15] R. Kapoor, R. Gupta, S. Jha, and R. Kumar, "Boosting performance of power quality event identification with KL Divergence measure and standard deviation," *Measurement*, vol. 126, pp. 134-142, 2018.
- [16] K. Thirumala, T. Jain, and A. C. Umarikar, "Visualizing time-varying power quality indices using generalized empirical wavelet transform," *Electric power systems research*, vol. 143, pp. 99-109, 2017.
- [17] A. Sharma, B. S. Rajpurohit, and S. N. Singh, "A review on economics of power quality: Impact, assessment and mitigation," *Renewable and Sustainable Energy Reviews*, vol. 88, pp. 363-372, 2018.s
- [18] J. Arrillaga, B. C. Smith, N. R. Watson, and A. R. Wood, *Power system harmonic analysis*. 2013.
- [19] P. Li, L. Xie, J. Han, S. Pang, and P. Li, "A new voltage compensation philosophy for dynamic voltage restorer to mitigate voltage sags using three-phase voltage ellipse parameters," *IEEE Transactions on Power Electronics*, vol. 33, no. 2, pp. 1154-1166, 2018.
- [20] P. Kumari and V. K. Garg, "Simulation of Dynamic Voltage Restorer Using Matlab to Enhance Power Quality in Distribution System," *Int. J. Eng. Res. Appl.*, vol. 3, no. 4, pp. 1436-1441, 2013.
- [21] A. Kazemi and A. Azhdast, "Implementation of a control strategy for dynamic voltage restorer(DVR) and dynamic voltage compensator(DVC)," *2009 IEEE/PES Power Syst. Conf. Expo. PSCE 2009*, no. Dvc, pp. 1-6, 2009.
- [22] H. Ezoji, A. Reza, M. Shahverdi, A. Ghatresamani, and M. Hosein, "Hysteresis Voltage Control of DVR Based on Unipolar PWM," in *Applications of MATLAB in Science and Engineering*, InTech, 2011.
- [23] D. K. Chaturvedi, *Modeling and simulation of systems using MATLAB® and simulink®*. 2017.
- [24] F. A. L. Jowder, "Modeling and simulation of Dynamic Voltage Restorer (DVR) based on hysteresis voltage control," *IECON Proc. (Industrial Electron. Conf.)*, pp. 1726-1731, 2007.
- [25] S. Rajesh, M. K. Mishra, S. M. Ieee, and K. Sridhar, "Design and Simulation of Dynamic Voltage Restorer (DVR) Using Sinusoidal Pulse Width Modulation (SPWM)," pp. 317-322, 2010.